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GB A 2093998 GB 1351390 US 4132110
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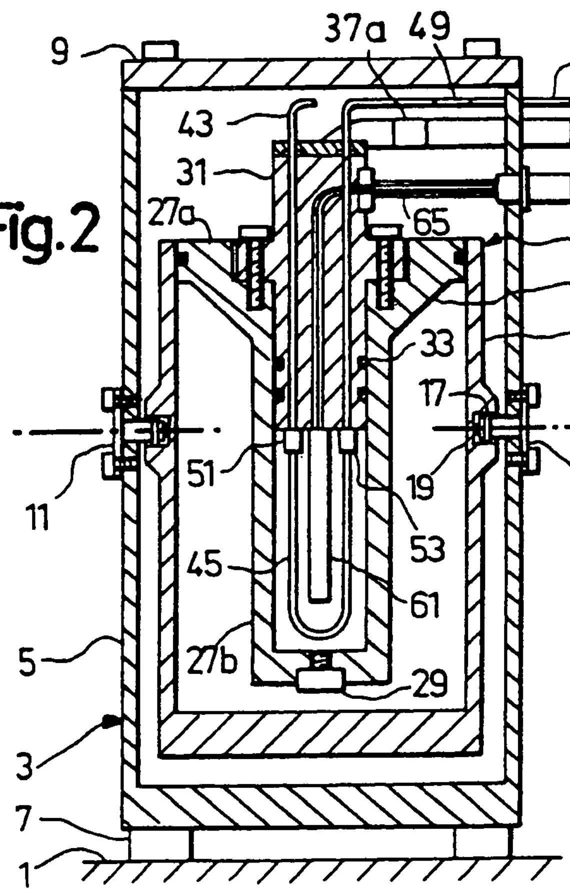
(58) Field of search
G1G
G1S
Selected US specifications from IPC sub-class G01N

(54) Fluid density measuring apparatus

(57) Fluid density measuring apparatus comprises a mechanical oscillator (45), which is formed by a portion of a bent tube (43) held at two places by a holder (31). An oscillation detector (51) and an oscillation exciter (53) are arranged in the proximity of these places and each comprises at least one respective piezo-electric element, which stands in effective connection with the oscillator (45). The detector (51) is electrically connected with the exciter (53) by way of a charge amplifier, an integrator and a correction phase shifter of an electronic device (61). When the oscillator (45), which is filled with the liquid of which the density is to be determined, is brought into oscillation, the integrator additionally to a voltage amplification effects a phase shift through a phase angle of about 90° and an attenuation of alternating voltages at high frequencies. The piezo-electric elements of the detector (51) and exciter (53) are insensitive to external magnetic fields, cause practically no frequency-dependent and/or temperature-dependent phase shifts and can be arranged near to the places at which the oscillator (45) is held in the holder (31), so that they hardly disturb the oscillations.

Fig.2



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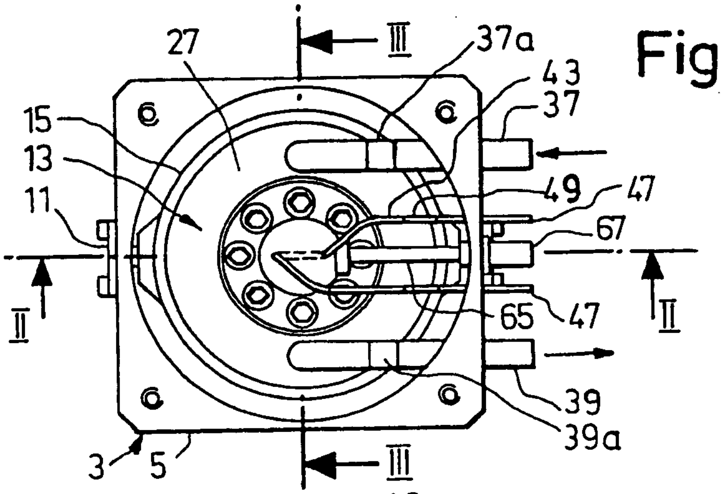

Fig. 1

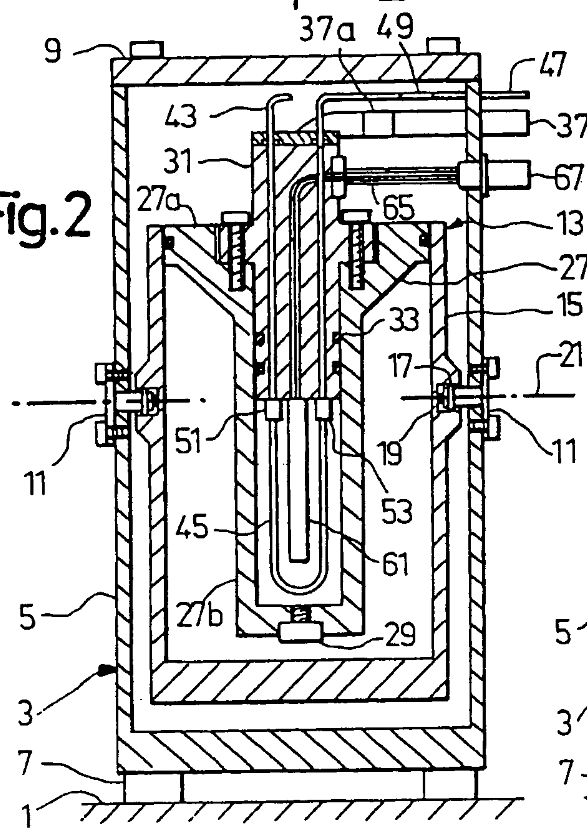

Fig. 2

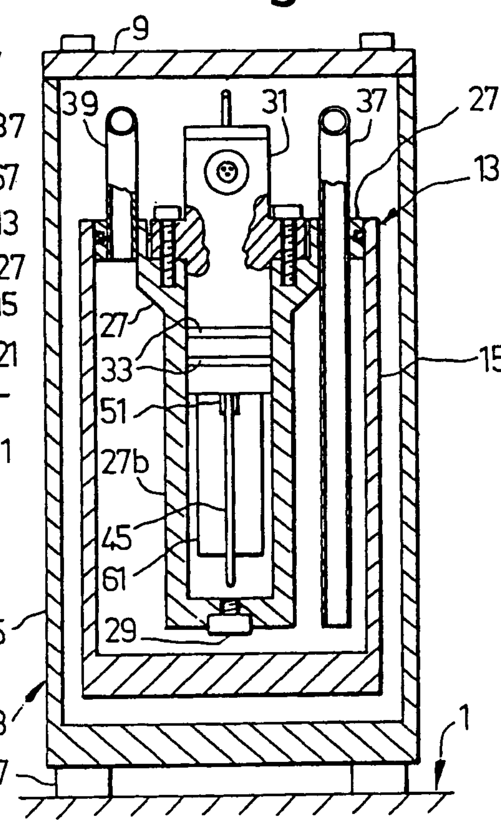

Fig. 3

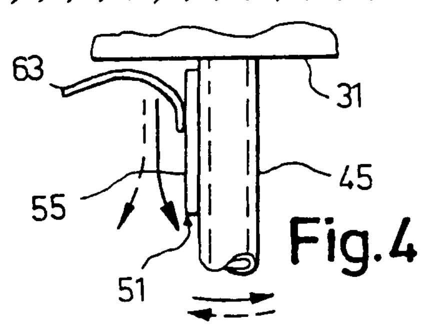

Fig. 4

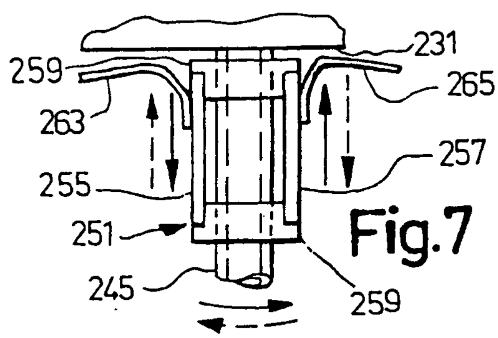

Fig. 7

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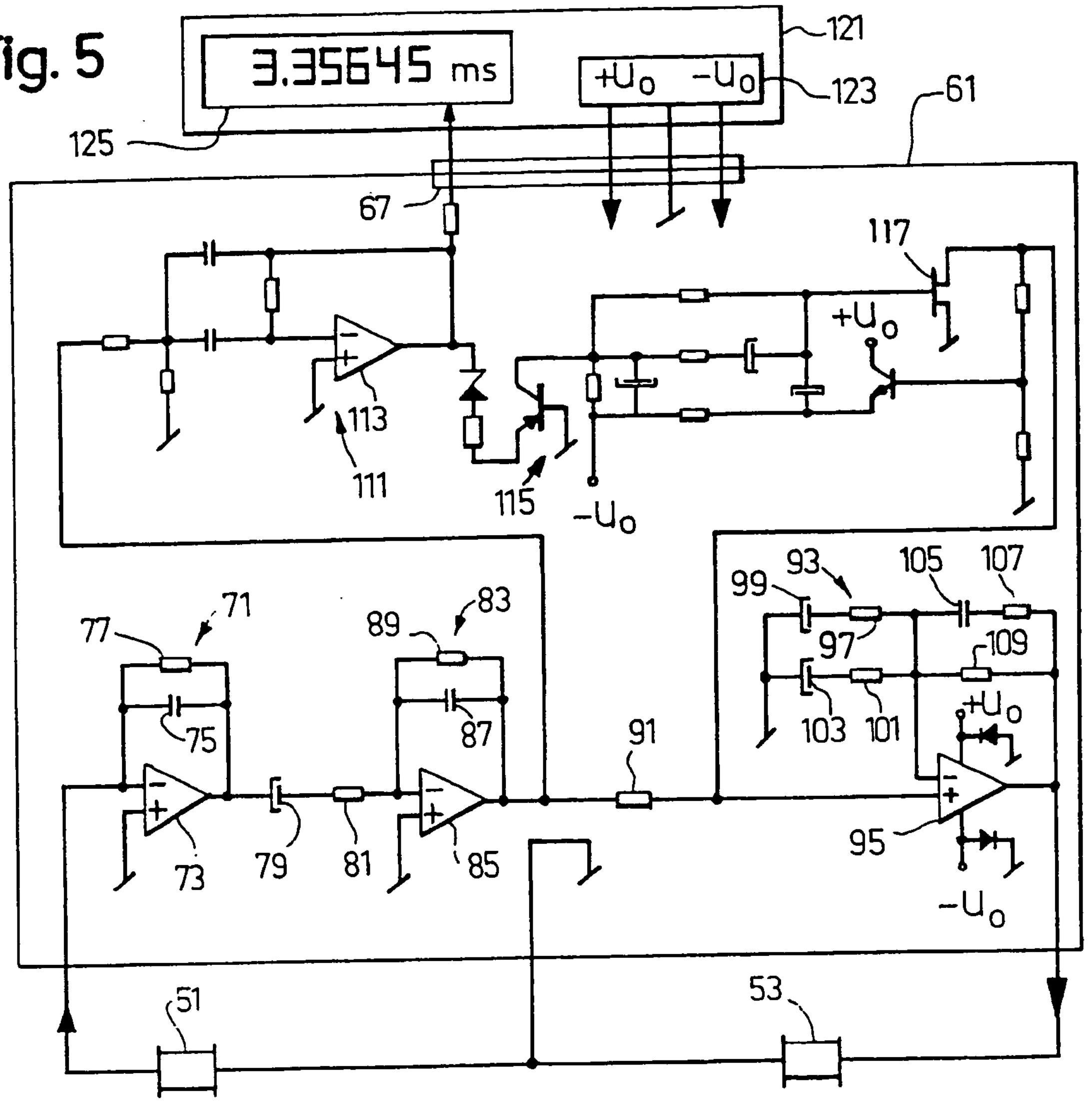
Fig. 5



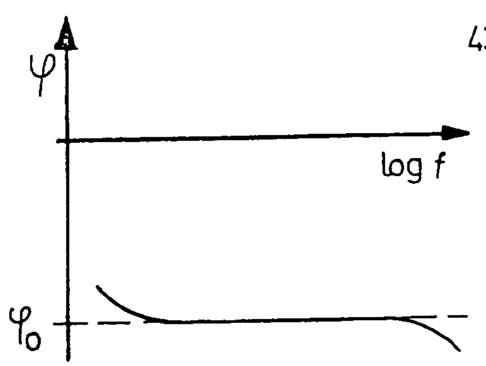


Fig.6

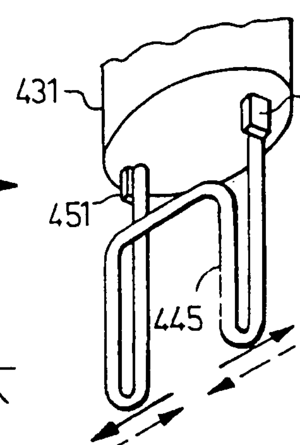


Fig.8

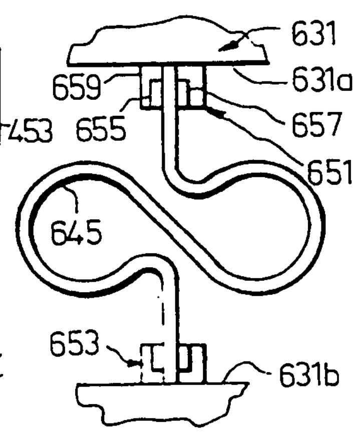


Fig.9

SPECIFICATION

Fluid density measuring apparatus

The present invention relates to fluid density measuring apparatus, especially apparatus for measuring the density of a gaseous, liquid or pasty material.

In Austrian Patent Specification No. 280 662 there is disclosed density measuring apparatus with a mechanical oscillator of glass. Fastened to the oscillator is a rod-shaped permanent magnet, the mutually remote end portions of which project as armatures into coils fastened to the carrier. One of the two coils, together with the associated armature, acts as an oscillation detector and is connected by way of an amplifier of an electronic device with the other coil which, together with the armature projecting into it, acts as an oscillation exciter. The detector voltage induced in the coil of the detector during performance of a measurement is amplified by the amplifier and fed as an excitation voltage to the coil of the exciter, wherein the force produced by the latter is in the ideal case equal in phase to the oscillation speed of the oscillator. The period duration then gives a measure for the density of a liquid or gaseous material in the oscillator body.

The coils have an impedance composed of an inductive reactance and an ohmic resistance. Since the ohmic resistance is dependent on temperature, temperature-dependent phase shifts can arise between the armature speeds and the voltage present across the coils. Moreover, the inductance gives rise to eddy currents which are dependent on the frequency and on the resistance of the materials through which they flow and thereby also on the temperature. These eddy currents accordingly can cause frequency-dependent and temperature-dependent phase shifts between the armature speeds and coil voltages. When the phase position of the excitation force changes with respect to the oscillation speed or deflection of the oscillator, the interlinking between density and period duration is thereby changed and causes measurement errors which are the greater the lower the quality of the mechanical oscillator. In the case of commercially known apparatus equipped with inductive oscillation detectors and oscillation exciters, the electronic device has been equipped with circuit means for reduction of the phase errors caused in the excitation oscillator in order to feed an impressed, regulable current to the coil of the exciter. However, this results in an appreciable increase in price and still does not provide complete exclusion of phase errors in the coils, because the errors arising in the coil of the detector cannot be reduced at all.

Since the armatures are arranged at a place disposed near the free end of the oscillator and also must be arranged at such a place to enable the attainment of an adequate stroke, the detector and exciter can impair the quality of the mechanical oscillator and disturb the oscillations as well as, in some circumstances, still cause phase errors. Moreover, inductive oscillation detectors and oscillation exciters can also be disturbed by external magnetic fields, which cannot be completely screened off even with substantial cost and complication.

In the ideal case, the mechanical oscillator would be fastened to an infinitely large, completely immobile rest mass. In the case of commercially known apparatus with inductive oscillation detectors as well as oscillation exciters, the carrier holding the mechanical oscillator is rigidly fastened to a housing that stands on any kind of support. During oscillation, the oscillator delivers energy to the carrier and the housing so that the latter two co-oscillate slightly. The resulting period durations of the oscillator then additionally depend on the coupling between the housing and the support carrying this. In order to minimise the influence of this coupling on the measurement results, it has been the practice to provide a relatively large total mass, for example at least 15 kilograms, of the carrier and the housing, which is disadvantageous. The commercially known apparatus are used for, for example, determination of the density of beverages. From this density and from the additionally measured refractive index, for example in the case of alcoholic beverages, the alcohol content can then be determined. The apparatus for the measurement of the density of beverages are calibrated with water and air, as is envisaged in Austrian Patent Specification No. 280 662. Since, however, the density of air differs relatively substantially from that of beverages, such a calibration method impairs measurement accuracy, particularly in view of the different error sources which are present in the known apparatus which have already been discussed.

There is thus a need for apparatus, for the determination of density, which may eliminate the disadvantages of the known apparatus and make possible an improvement in measurement accuracy without undue cost. In that case, above all, the errors caused in the known apparatus through changes in frequency as well as temperature and external magnetic fields in the oscillation detectors and exciters should be eliminated as far as possible.

According to one aspect of the present invention there is provided fluid density measuring apparatus comprising a carrier, a mechanical oscillator held by the carrier and having a chamber for fluid, an oscillation exciter operatively connected to the oscillator to induce oscillation thereof, an oscillation detector operatively connected to the oscillator to provide an electrical detection signal indicative of such

oscillation, and an electronic device electrically connecting the detector to the exciter and operable to supply an electrical excitation signal to the exciter, the exciter and detector each comprising at least one respective piezo-electric element and the electronic device comprising circuit means to produce a phase shift between the detection signal and the excitation signal.

According to another aspect of the invention there is provided a method of calibrating apparatus of the kind referred to in the preceding paragraph, the method comprising the steps of introducing water and an alcohol of known density into the fluid chamber of the oscillator, inducing oscillation of the oscillator, and determining the magnitudes of or magnitudes dependent on the oscillation period durations.

In the apparatus, the electronic device comprises circuit means in order to produce, between the excitation signal and the detector signal, a phase shift which, in the frequency range in which the oscillation frequencies vary in the provided density-measuring range and which can be at least about 20% and for example at least or approximately 30% of the highest provided oscillation frequency, has an amount or absolute value which expediently departs at most about ±5°, preferably at most ±3° or even at most only ±1°, from the desired ideal value of 90°. This phase shift amount or absolute value is preferably as nearly as possible independent of the frequency and, for example, departs at most ±0.3%—even only at most ±0.1%—from a mean value in the stated frequency range. The circuit means preferably includes an integrator which, apart from a phase shift amounting in the ideal case to at least approximately 90°, also serves as a lowpass filter and yields a voltage amplification with an amplification factor of, for example, about 2 to 5.

Embodiments of the present invention will now be more particularly described by way of example with reference to the accompanying drawings, in which:

Fig. 1 is a plan view of density measuring apparatus embodying the invention, wherein a cover of a housing of the apparatus has been removed;

Fig. 2 is a vertical sectional view of the apparatus along the line II-II of Fig. 1;

Fig. 3 is a vertical sectional view of the apparatus along the line III-III of Fig. 1;

Fig. 4 is a detail, to an enlarged scale, from Fig. 3, showing a side elevation of a piezo-electric element arranged at an oscillator of the apparatus;

Fig. 5 is a circuit diagram of an electronic device present in the apparatus;

Fig. 6 is a diagram illustrating the phase-frequency relationship of the electronic device;

Fig. 7 is a side elevation, corresponding to that of Fig. 4, of a modified arrangement of piezo-electric elements;

Fig. 8 is a schematic view, seen obliquely from below, of a tuning-fork form of oscillator in one modification of the apparatus; and

Fig. 9 is a schematic view of an oscillator, for the performance of torsional oscillations, in another modification of the apparatus.

Referring now to the drawings, there is shown in Figs. 1 to 3 apparatus which serves for the measurement of the density of a gaseous, liquid or pasty material capable of flow, but particularly, for example a beverage. The apparatus comprises a carrying device 3, standing freely on a firm support 1, with a housing 5, which possesses four walls and which is provided at the bottom with feet 7, for example having slightly resilient rubber spigots, and at the top with a cover 9 detachably fastened by screws. Arranged at mutually opposite walls of the housing 5 are bearings 11, each of which comprises a flange attached by screws and a cylindrical spigot projecting through a hole in the respective wall of the housing 5 and into the interior space thereof. Arranged in the housing 5 is a carrier 13, which is separated from the material surface of the housing at least generally by an air space, i.e. a free intermediate space containing air, with a thermostat or water jacket chamber 15 having a bottom and a wall. The chamber 15 at each of two diametrically opposite locations has a respective cylindrical blind bore, into which projects the spigot of a respective one of the bearings 11. A rubber-elastic insulating and damping body 17, formed by an O-ring, is arranged between the circumferential surface of each of the spigots and the blind bore wall surface co-axial therewith and a rubber-elastic spherical insulating and damping body 19 is arranged between the free end face of each of the spigots and the base of the associated blind bore. Thetwo bearings 11 serve for radial as well as the axial bearing of the carrier 13 and together define an horizontal axis 21 about which the carrier 13 is pivotable, wherein the insulating and damping bodies 17 and 19 allow pivotal movement as well as limited axial movement of the carrier 13 and damp these somewhat.

An oscillation chamber 27 possesses a cover part 27a, which at the upper end of the chamber 15 is rigidly and, for example, detachably connected therewith and closes off the interior space thereof tightly, and a hollow sleeve-like finger 27b, which projects downwardly away from this and the lower closure wall of which has a bore provided with an internal thread and closed off detachably and in gas-tight manner by a screw 29 and, for example, a closure formed by a sealing ring (not shown). An oscillator holder 31 has a flange which sits in a depression in the cover part 27a and is detachably and rigidly fastened thereto by screws, and a projection

projecting into the interior space of the oscillation chamber 27 as far as the axis 21. The circumferential surface of this projection has two grooves, in each of which is arranged a respective rubber-elastic sealing ring 33, i.e. an O-ring, so that the oscillator holder 31 together with the sealing rings 33 closes off the lower free interior space of the oscillation chamber 27 in gas-tight manner upwardly.

The free interior space of the chamber 15 is connected with a feed duct connection 37 and a drainage duct connection 39, which are led outwardly through a wall, also holding one of the bearings 11, of the housing 5 and include deformable connection pieces 37a and 39a, such as hoses, between their portions fastened to the thermostat chamber and the housing wall. The connections 37 and 39 are connected with a temperature-regulating device (not shown) which is arranged to keep a liquid, namely water, at a predetermined temperature and conducted through the free interior space of the thermostat chamber 15. This is thermally insulated from the environment by the air space present between it and the housing 5 as well as by the insulating and damping bodies 17 and 19.

A one-piece tube 43, which consists of metal, namely stainless steel, extends in the free interior space of the oscillation chamber 27 and forms a U-shaped mechanical oscillator 45 with a hollow space, i.e. the bore of the tube. The two limbs, extending upwardly from the oscillator 45, of the tube 43 penetrate two mutually parallel and vertical passages in the holder 31 and are fastened rigidly to the holder by, for example, collets (not shown), which are screwed into the carrier 31 and have clamping cheeks, or by hard-soldering or gluing. In that case, preferably at least the lower end portions of the two passages in the holder have internal diameters agreeing at least approximately with the external diameter of the tube limbs so that the limbs fit therein radially free of play. The portions of the limbs projecting out from the holder 31 are each connected by way of a deformable connecting piece 49, for example a hose, with a horizontally extending connection 47 penetrating the same wall of the housing 5 as the connections 37 and 39. The deformable connecting pieces 37a, 39a and 49 allow the carrier 13 to execute limited movement and above all small pivotal movement with respect to the housing 5 in spite of the ducts connecting the housing 5 and the carrier 13 with each other.

An oscillation detector 51 is arranged on one limb of the U-shaped oscillator 45 and an oscillation exciter 53 is arranged on the other limb. The detector 51, drawn to larger scale in Fig. 4, and the exciter 53 each comprise a platelet-shaped, piezo-electric element 55 as main component. Both elements 55 are on one side of the oscillator, namely on the same side of the vertical plane spanned by the U-shaped axis of the oscillator 45 when disposed in its rest position, and externally fastened thereto over their entire length extending along the respective oscillator portion, in particular soldered or glued on. The elements 55 can be constructed as, for example, so-called bimorph elements which possess two piezo-electrically effective platelets fastened to each other and which, during bending, generate an electrical voltage or are bent through application of an electrical voltage and thus respond to bending forces and/or bending moments or generate such. In piezo-electric elements, the conversion of force into electrical voltage and conversely takes place with relatively small deformation so that they provide almost pure force-voltage conversions, i.e. nearly free of stroke and travel. Consequently, the detector 51 and the exciter 53 can be arranged in the proximity of the boundary plane or surfaces at which the oscillator limbs penetrate into the holder 31 and which delimit the limb portions capable of oscillation from the limb portions fastened rigidly in the holder 31. These boundary surfaces, which lie at least approximately and preferably exactly in the same horizontal plane as the àxis 21, form oscillation nodes, namely nodal surfaces, when the oscillator 45 oscillates at its basic resonant frequency. The maximum spacing of the engagement points of the detector 51 and of the exciter 53 from the nodal surfaces shall be at most 20% of the dimension measured from the horizontal nodal surfaces to the point of the oscillator 45 furthest from this, i.e. the lowermost point of the U-arc along the axis of the tube portion forming the oscillator, namely half the length of the oscillator.

Also fastened to the holder 31 is an electronic device 61, the individual parts of which are, for example, formed by a casting mass into a compact block and which is disposed in the free interior space of the oscillation chamber 27 between the limbs of the oscillator 45, from which it is, however, separated by free intermediate spaces. The piezo-electric elements forming the detector 51 and exciter 53 respectively each have two connections, of which one is connected by way of the metallic oscillator 45 with the ground connection of the electronic device 61 and the other by way of a respective separate conductor, which in Fig. 4 is designated by 63 for the detector 51, with the electronic device 61. This in turn is connected by a multiple line 65, which extends in part through a passage in the holder 31, with a plug 67 fastened to the same wall of the housing 5 as the connections 37, 39 and 47. The line 65 is in that case cast in gas-tight manner in the passage in the holder 31 and between the holder 31 and the plug 67 sufficiently flexibly so that pivotal movement of the carrier 13 is possible. The free interior space of the chamber 27 contains he-

lium or another gas, such as hydrogen, which provides a good thermal conduction and which introduced through the hole closable by the closure 29.

The electronic device 61, the circuit diagram of which is illustrated in Fig. 5, comprises a charge amplifier 71 with an operational amplifier 73, the non-inverting input of which is connected with the ground connection and the inverting input of which is connected with the non-grounded connection of the detector 51 and by way of a negative feedback member, which consists of a capacitor 75 and a resistor 77 connected in parallel therewith, with the output of the amplifier 73. The amplifier output is connected by way of a capacitor 79 and a resistor 81 connected in series therewith with the inverting input of an operational amplifier 85, which is part of an integrator 83 and the non-inverting input of which is connected with the ground connection. The output and the inverting input of the amplifier 85 are each connected with the other through a negative feedback member with a capacitor 87 and a resistor 89 connected in parallel therewith. The output of the amplifier 85 is connected by way of a resistor 91 with the non-inverting input of an operational amplifier 95, which together with a resistance-capacitance network forms a correction phase shifter 93. The inverting input of the amplifier 95 is connected to the ground connection by way of two parallelly connected branches of the network with respective resistors 97 and 101 and respective capacitors 99 and 103 connected in series therewith, and to the output of the amplifier 95 by way of two parallelly connected network branches, of which one has a capacitor 105 and a resistor 107 connected in series therewith and the other only a resistor 109. The output of the amplifier 95 is also connected with the non-grounded connection of the exciter 53.

The output of the amplifier 85 of the integrator 83 is also connected with an active band-pass filter 111, which comprises an operational amplifier 113 and a resistance-capacitance network applying negative feedback thereto. The output of the filter 111 is connected with the input of a regulator 115, namely a proportional-integral-differential (PID) regulator. This has a field effect transistor 117, the "drain" connection of which is connected on the one hand with a linearising circuit having a voltage divider and a transistor serving for linearisation and on the other hand with the non-inverting input of the amplifier 95, and which together with the linearising circuit as well as the resistor 91 serves as a setting member.

The ground connection of the electronic device 61 is also electrically conductively connected with the metallic parts of the housing 5 and carrier 13. The plug 67 has three connections, which are insulated from its housing serving as ground connection, and is electrically connected separably with a separate electronic device 121 by way of a counterplug and a cable. This electronic device 121 comprises a current supply device 123 in order to feed a direct voltage $+U_0$ positive to ground as well as a voltage $-U_0$ negative to ground to the electronic device 61, and an evaluating device 125.

When the density of a sample, for example of a beverage, is to be measured, the tube 43 is filled by the beverage up to the uppermost places of its limbs so that the oscillator 45 is filled. The beverage disposed in the oscillator is then brought to the temperature, for example 20°C, of water conducted through the thermostat chamber. The electronic device 61 is set into operation through actuation of a switch of the evaluating device and the oscillator 45 is thereby induced to oscillate.

The carrier 13 is dimensioned in such a manner that the centre of mass of the parts of the carrier itself, of the water present in the thermostat chamber, of the oscillator 45 and of the beverage present in this is disposed at least approximately on the axis 21 and centrally between the limbs of the oscillator 45. When the oscillator 45 executes bending oscillations along a plane at right angles to the axis 21, the carrier 13 can execute small pivotal movements in opposite sense about the axis 21, which at least to a large extent compensate for the turning moments transmitted by the oscillator 45 to the carrier. The insulating and damping bodies 17 and 19 damp the movement of the carrier 13 so that the carrying device 3 and the carrier 13, even when they have only relatively small masses, behave in similar manner to an infinitely large rest mass. When the tube 43 forming the oscillator 45 has, for example, an external diameter of 2 millimetres and a wall thickness of 0.1 millimetres, the oscillator 45 together with its filling can have a mass in the order of 1 gram. The total mass of the carrying device 3 and of the parts held by it can then be less than 10 kilograms, for example about 5 to 7 kilograms.

When the oscillator 45 oscillates during the determination of a density, it is bent alternately along a plane at right angles to the axis 21 in the directions designated in Fig. 4 by the lower arrow drawn in a solid line and the lower arrow drawn in a dashed line. In that case, at least the two limbs of the oscillator and possibly also its remaining, arcuate portion are deformed resiliently. The piezo-electric element 55 of the detector 51 is also bent and assumes alternate shapes likewise indicated schematically in Fig. 4 by the upper arrow drawn in a solid line as well as the upper arrow drawn in a dashed line. The element then generates, in dependence on time at the oscillation frequency of the oscillator 45, a periodically and sinusoidally changing electrical

detector signal, namely a changing charge and an alternating voltage connected therewith. The electronic device 61 forms from the detector signal in a manner yet to be described in detail, through amplification, phase rotation and regulation an electrical excitation signal. This signal is formed by an alternating voltage and changes periodically as well as sinusoidally in dependence on the time, and is conducted by the device 61 to the exciter 53. The piezo-electric element 55 thereof is thereby bent alternately in different directions and exerts a temporally changing excitation force, namely a bending force and thereby also a bending moment, on the oscillator 45.

The deflection and the acceleration of the oscillating oscillator 45 are displaced relative to each other through a phase angle of 180'. In order that the oscillator 45 oscillates at its resonant frequency or, more accurately, its basic resonant frequency, the excitation force must lag the acceleration of the oscillator through a phase angle of 90° and lead the deflection of the oscillator through a phase angle of 90°.

The detector signal generated by the detector 51 can, according to the polarity of the connections or fastening of the piezo-electric element 55, be equal in phase to the deflection of the oscillator or be displaced through 180° thereto and accordingly be equal in phase to the acceleration. The same applies to the relationship between the excitation voltage fed to the piezo-electric element 55 of the exciter 53 and the excitation force. In the present case, the piezo-electric elements of the detector and exciter are arranged with the same polarity and the positive direction of the deflections, accelerations and forces shall be defined in such a manner that the detector signal is equal in phase to the acceleration of the oscillator. The excitation force is then, as required, equal in phase to the excitation signal.

The invertingly connected operational amplifier 73 of the charge amplifier 71 serving for impedance matching feeds a voltage, which in the ideal case is rotated through a phase angle amounting to 180° relative to the detector signal, to the integrator 83. The amplifier 85, also connected to be inverting, of the integrator 83 amplifies the voltage fed to it by an amplification factor of, for example, 2 to 5 and rotates the phase through a phase angle of 180°. In addition, the electrical integration process effects a phase delay, the phase angle of which in the ideal case has an amount or absolute value of 90°. The amplifier 95 of the correction phase shifter 93 yields once again a voltage amplification with an amplification factor of, for example, 2 to 10. Since the amplifier 95 is connected to be non-inverting, the excitation signal fed by it to the exciter 53 would be rotated relative to the detector signal through a phase angle of 90°, and lagging, if merely the phase rotations were to take place, which are stated in the preceding, simplified and idealised description. The bending excitation force exerted by the exciter 53 on the oscillator 45 is thus in the ideal case lagging relative to the acceleration of the oscillator 45 through a phase angle amounting to exactly 90° and leading relative to the deflection of the latter through 90°, so that the oscillator oscillates exactly at its resonant frequency.

The integrator 83 results not only in an amplification and phase rotation, but also still acts as a low-pass filter which attenuates alternating voltages of great frequencies. The upper limit frequency of the low-pass filter is given, as is the integration time constant of the integrator, by the resistor 81 and the capacitor 87 and is fixed to a value lying above the basic resonant frequencies, resulting in the measurement range, of the oscillator. The upper limit frequency of the low-pass filter formed by the integrator 83 is preferably at least three times and at most thirty times, for example five to fifteen times, the highest envisaged basic resonant frequency of the oscillator 45. The oscillator can have, for example, basic resonant frequencies of 350 to 500 hertz in the provided measuring range. The resistor 81 can in this case have a resistance value of 33 kilo-ohms and the capacitor 87 a capacitance of one nanofarad so that an integration time constant of 33 microseconds and an upper low-pass basic frequency of approximately 4.8 kilohertz result. Due to the fact that the integrator 83 effects, additionally to the 90° phase angle rotation, an attenuation of alternating voltages of great frequencies, it is ensured that the oscillator 45 always oscillates at its basic resonant frequency and not at a harmonic, i.e. a resonant frequency of higher order.

In the illustrated embodiment, the capacitors 75 and 79 have a capacitance of 33 picofarads and 1 microfarad, respectively, and the resistors 77 and 89 have resistance values of 1 giga-ohm and 33 megohms, respectively. The three capacitors 75, 79 and 87 together with the resistors 77 or 81 or 89 each form a respective capacitor-resistor pair, each of which determines a limit frequency of approximately 4.8 hertz. These limit frequencies are thus substantially smaller than the oscillator frequencies resulting during the measurement of densities. The different co-operating capacitors and resistors of the charge amplifier 71 and integrator 83 cause frequency-dependent phase rotations or displacements in addition to the phase rotations stated in the preceding simplified functional description of the electronic device 61. These altogether have the effect that the phase angle, through which the voltage supplied by the integrator lags the detector voltage, does not have a constant value of 90°, but becomes greater in terms of value

with increasing frequency.

In the present embodiment, the resistor 91 has a resistance value of 10 kilo-ohms, the resistor 97 a resistance value of 33 kilo-ohms, the resistor 101 a resistance value of 6.8 kilo-ohms, the resistor 107 a resistance value of 6.8 megohms and the resistor 109 a resistance value amounting to 2.2 megohms. Moreover, the capacitor 99 has a capacitance of 1 microfarad and the capacitor 105 a capacitance of 33 picofarads. The correction phase shifter 93 then effects a phase rotation, the frequency dependence of which in the provided measuring range is of opposite sense to the frequency dependence of the phase rotation produced by the charge amplifier and integrated together and compensates for this at least approximately. If the phase angles are represented as a variable dependent on frequency and a negative value is allocated to the one phase delay, i.e. phase angles representing lagging, and a positive sign to the one phase advance, i.e. phase angles representing leading, a negative slope results for the phase displacements or rotations caused by the charge amplifier 71 and integrator 83 and a positive slope for the phase angle of the phase rotations effected by the correction phase shifter in the provided measuring range.

In Fig. 6, the logarithm of the frequency f of the oscillations of the oscillator 45 is entered on the abscissa and the phase angle ϕ, through which the excitation signal is displaced relative to the detector signal, is entered on the ordinate. Fig. 6 also shows a curve which represents the qualitative frequency dependence of the phase angle ϕ for the described embodiment of the electronic device 61. The curve at least in the provided measuring range, i.e. at least at oscillation frequencies of 350 to 500 hertz, has a plateau at which the phase angle ϕ has an at least approximately constant mean value ϕ_o of about $-89.3°$ and departs from this by at most about $\pm$ 0.1°.

The splitting up of the amplification ofthe detector signal to the magnitude required for the excitation signal for the maintenance of the oscillator oscillations over several operational amplifiers 73, 85 and 95, which are individually provided with feedback and form an amplifier chain and of which the middle amplifier 85 of the integrator 83 effects a phase shift amounting to approximately 90°, contributes to the prevention of instabilities, i.e. of oscillations which could arise through an oscillator effect of the circuit means chain connecting the detector 51 with the exciter 53.

The alternating voltage produced by the integrator 83 is also fed to the input of the band-pass filter 111. This is constructed in such a manner that it passes alternating voltages of the frequencies resulting in the provided measuring range. Thereagainst, interference voltages, caused for example through shocks, at frequencies below the pass range, as well as interference voltages which have, for example, arisen through noise effects and which have frequencies above the pass range, are suppressed. The voltage present at the output of the filter 111 is then fed as a regulating magnitude, interlinked with the detector signal and having an amplitude proportional to the signal amplitudes, to the regulator 115, the setting member 91 and 117 of which regulates the voltage transmitted from the amplifier 85 to the amplifier 95 in such a manner that the amplitudes of the detector signal and thereby the amplitudes of the oscillations of the oscillator 45 remain constant.

The output voltage of the filter 111 is also fed by way of a coupling resistor to the evaluating device 125. This can comprise, for example, an oscillator, which serves as a timing generator, and circuit means in order to determine the time duration, which elapses during a fixedly predetermined number—for example approximately 5000—of oscillations of the oscillator and which is, of course, proportional to the oscillation period duration. The evaluating device then shows, for example, the period duration T of the oscillations by a digital indicating device, possibly in milliseconds. When c and k are two constants, the relationship between the density ρ to be measured and the period duration T can be represented by the formula:

$$\rho = cT^2 - k.$$

The two constants c and k can be determined through calibration in that the resultant period durations are ascertained for two calibration liquids of known densities. When the densities of alcoholic beverages containing water and alcohol are to be determined, distilled water and an alcohol, possibly n-propylalcohol, can be employed as calibration liquids, the densities of which are approximately 1 gram per cubic centimetre and approximately 0.8 grams per cubic centimetre, respectively, and thus lie relatively close to the densities to be measured. The evaluating device 125 can include a calculator with stores as well as means for the input of numbers and can be constructed to indicate and/or print out, additionally to the period duration or instead thereof, the density to be measured and/or any other magnitude linked with the period duration.

Since the detector 51 and the exciter 53 are arranged relatively close to the oscillation nodes of the oscillator 45, they have practically no interference effect on the oscillations thereof, which contributes to the attainment of a high accuracy factor, of at least about 400, of the oscillator. Also, of course, no phase shifts due to resistance changes caused through temperature changes or external magnetic fields can arise in the piezo-electric ele-

ments of the detector 51 and exciter 53, as was otherwise the case with the inductive detectors and exciters used in prior art apparatus. The piezo-electric elements therefore cause no, or practically no, frequency-dependent and/or temperature-dependent phase shifts.

When an accuracy factor of, for example, approximately 900 is achieved for the oscillator 45, a change of the phase angle ϕ present between the excitation signal and the detector signal by 1° effects a change in the oscillation frequency of the oscillator of about 0.001%. As mentioned in the preceding, the mean value ϕ_o, which results in the measuring range in the described embodiment, of the phase angle departs by less than 1° from the ideal value of the phase angle with the absolute value or amount of 90°. The deviation of the mean value ϕ_o can, however, be eliminated by the mentioned calibration. The frequency-dependent change of the phase angle of at most ±0.1° resulting in the measuring range can then change the oscillation frequency through at most approximately ±0.0001%. The density of the beverage in the hollow space of the oscillator 45 is, of course, dependent on the temperature thereof. The water led through the thermostat chamber 15 for the attainment of a predetermined temperature—for example 20°C—of the beverage does, of course keep the detector 51 and exciter 53 as well as the electronic device 61 at the same temperature. When the temperature of the beverage in the oscillator 45 is brought by means of the water conducted through the thermostat chamber 15 to the predetermined value of, for example, 20° with an accuracy of 0.1°K or even 0.01°K, the density of the beverage can be readily determined with a measurement error of at most 0.001% or at most 0.0001%. In the case of an alcoholic beverage, the alcohol content thereof can then be calculated from the density and the additionally determined refractive index, wherein this calculation can possibly be undertaken by the calculator of the evaluating device 125.

Fig. 7 shows a detail of a variant of the apparatus with a holder 231 and an oscillator 245, which can be constructed and fastened in similar manner to the oscillator 45. An oscillation detector 251 comprises two annular holding elements 259, which are fastened to the oscillator 245, possibly soldered on or clamped fast, and two piezoelectric elements 255 and 257 in the form of small plates or rods. These are fastened by their ends to a respective one of the two holding elements 259, possibly soldered or glued on, at mutually remote sides of the oscillator 245 and separated therefrom, for example by an intermediate space. Each has two connections, of which one is connected by way of the metallic oscillator 245 and the other by way of a conductor 263 or 265 with the electronic device.

When the oscillator 245 executes bending oscillations during determination of a density and bends alternately in one of the directions designated by the arrow in a solid line and the arrow in a dashed line, each of the piezoelectric elements 255 and 257 is alternately expanded and compressed parallelly to the axis of the oscillator portion adjacent thereto, as is indicated by arrows drawn in solid and dashed lines. The piezo-electric elements each comprise only a respective single piezo-electric platelet and are constructed in such a manner that they generate an electrical detector signal on occurrence of the mentioned dimensional changes along the axis of the oscillator portion disposed therebetween. Since the piezoelectric elements 255 and 257 are deformed in opposite sense, their connections can be connected electrically in parallel with opposite polarity and be connected with the input of the charge amplifier and the ground connection of the electronic device, respectively. Of course, it would also be possible to connect the elements 255 and 257 electrically in series. The oscillation exciter can be provided with two piezo-electric elements 255 and 257, which are arranged in analogous manner and change their dimensions on the application of an excitation signal.

In addition, it is possible to provide only one piezo-electric element respectively in the case of the detector 251 and the exciter, for example only the piezo-electric element 255. Furthermore, piezoelectric elements, which in the case of a dimensional change parallelly to a straight line generate an electrical detector signal or are deformable correspondingly by an electrical excitation signal, could also lie against the oscillator and be fastened directly to this analogously as the elements 55.

The variant of the apparatus, of which some parts are illustrated schematically in Fig. 8, comprises a holder 431, a mechanical oscillator 445 fastened at this, an oscillation detector 451 and an oscillation exciter 453. The oscillator 445 consists of a tube which is bent in such a manner that, together with the holder 431, it forms a fork with two tines which as in the case of a tuning fork oscillate towards and away from each other in the directions indicated by arrows. The detector 451 and the exciter 453 are each arranged in the proximity of a respective fastening point of the oscillator and each comprise at least one respective piezo-electric element, which can be constructed as the element 51 or as the elements 255 and 257. Since the oscillator 445 during oscillation delivers almost no energy to the holder 431 and has a correspondingly large quality factor, the carrier, to which the holder belongs, can in this case be connected rigidly with the carrying device standing on a support. If the carrier, in spite of the lower energy delivery ofthe oscillator, is still to be pivotably mounted at the carrying de-

vice, the pivot axis would have to be arranged at right angles to the plane along which the tines of the oscillator oscillate.

Illustrated in Fig. 9 are schematic parts of apparatus comprising an oscillator holder 631 which has two parts 631a and 631b, which are rigidly connected with each other in any manner, and an oscillator 645. This is formed by a tube which has an S-shaped portion and limbs which project away from this on mutually opposite sides, are fastened respectively in the parts 631a and 631b of the holder 631 and which have a common axis so that the oscillator 645 can execute torsional oscillations therearound. An oscillation detector 651 and an oscillation exciter 653 each comprise a respective holding element 659, which is fastened respectively to the part 631a and the part 631b, and two piezo-electric elements 655 and 657. The latter engage at one end at the holding element 659 and at the other tangentially at circumferential points of the oscillator 645 and are constructed and electrically connected with an electronic device in such a manner that, in the case of dimensional changes at right angles to the axis about which the oscillator 645 executes torsional oscillations, they generate an electrical detector signal or under the influence of an electrical excitation signal exert a torsional excitation force on the oscillator. The carrier, to which the holder 631 belongs, can be held either rigidly or pivotably at a carrying device corresponding to the carrying device 3. In the case of a pivotal connection, the pivot axis thereof should be parallel to the axis about which the oscillator 645 can oscillate, and, for example, coincide at least approximately with this last-mentioned axis.

The apparatus can be altered in other respects. The electronic device could be arranged not in the free hollow space of the oscillator chamber but in the interior of a portion, still enclosed by the thermostat chamber, of the holder holding the oscillator, where it is still held at a constant temperature by the water conducted through the thermostat chamber.

When only relatively low demands are made on the measurement accuracy, the thermostat chamber can be dispensed with as well as the circulation of a liquid at a temperature regulated to a constant value and a chamber which is filled with helium and tightly encloses the oscillator.

The circuit of the electronic device can also be altered in various ways. For example, the charge amplifier 73 could be replaced by a differently constructed impedance converter, possibly a field effect transistor connected as follower. A pulse shaper could be arranged in the connection connecting the output of the band-pass filter with the evaluating device in order to feed a pulse sequence in place of an alternating voltage to the evaluating device. Moreover, the correction phase shifter could be arranged in front of the integrator with respect to the signal flow direction. Furthermore, the network of the correction phase shifter 93 could be modified in the sense that the mean value of the phase shift between the excitation signal and the detector signal is exactly 90° in terms of amount in the measuring range.

In addition, the operational amplifier of the integrator could be connected to be non-inverting, wherein that connection of the resistor 81, which is connected with the capacitor 79, would be connected with the ground connection instead of with the capacitor 79 and the non-inverting input of the amplifier 85 would be connected by way of a resistor with the capacitor 79 instead of with the ground connection. The operational amplifier of the correction phase shifter could also be connected to be inverting and/or an additional amplifier could be present in the amplifier chain connecting the detector with the exciter. If changes of that kind are undertaken, approximately the same phase shift as for the electronic device 61 or an additional shift of 180° could result between the excitation signal and the detector signal according to the number of voltage inversions in the amplifier chain connecting the detector with the exciter. In order that the correct phase position of the excitation force with reference to the acceleration and deflection of the oscillator still results in the latter case, the polarity of the or each piezo-electric element could be reversed either in the detector or in the exciter or the arrangement of the piezo-electric elements could be changed with respect to the oscillator.

The apparatus can be employed not only for the measurement of the density of alcoholic beverages, such as wines, beers and spirits, but also for the determination of the density of other liquids containing water and alcohol, in which the alcohol content can then be also determined through an additional measurement of the refractive index. The apparatus can also serve for the determination of the density of alcohol-free beverages, such as fruit juices or other liquid, pharmaceutical materials and even pasty materials, for example tomato ketchup or creams and ointments for pharmaceutical and cosmetic purposes. Finally, the density of gaseous materials can also be determined.

CLAIMS

1. Fluid density measuring apparatus comprising a carrier, a mechanical oscillator held by the carrier and having a chamber for fluid, an oscillation exciter operatively connected to the oscillator to induce oscillation thereof, an oscillation detector operatively connected to the oscillator to provide an electrical detection signal indicative of such oscillation, and an electronic device electrically connecting the detector to the exciter and operable to supply an

electrical excitation signal to the exciter, the exciter and detector each comprising at least one respective piezo-electric element and the electronic device comprising circuit means to produce a phase shift between the detection signal and the excitation signal.

2. Apparatus as claimed in claim 1, the circuit means comprising an integrator.

3. Apparatus as claimed in claim 2, wherein the integrator comprises an operational amplifier and a negative feedback member which connects the output of the amplifier to the inverting input of the amplifier and which comprises a capacitor.

4. Apparatus as claimed in claim 3, wherein the feedback member comprises a resistor connected in parallel with the capacitor.

5. Apparatus as claimed in any one of claims 2 to 4, wherein the electronic device comprises an impedance transformer connecting the detector to the integrator.

6. Apparatus as claimed in claim 5, wherein the transformer comprises a charge amplifier.

7. Apparatus as claimed in any one of claims 2 to 6, wherein the electronic device comprises a correction phase-shifter connected in series with the integrator to produce a phase shift, the phase angle of which increases with increasing frequency in a frequency range when positive phase angles are associated with phase shifts effecting a lead and negative phase angles are associated with phase shifts effecting a lag.

8. Apparatus as claimed in claim 7, wherein the correction phaseshifter is connected between the integrator and the exciter.

9. Apparatus as claimed in either claim 7 or claim 8, wherein the correction phase-shifter comprises an operational amplifier and a resistance-capacitance network connecting the output of that amplifier to the inverting input of that amplifier.

10. Apparatus as claimed in any one of the preceding claims, wherein the electronic device comprises a regulator to so regulate the magnitude of the excitation signal that the oscillations of the oscillator have a substantially constant magnitude, and a band-pass filter connected at its input to a connection between the detector and the exciter and at its output to the regulator to supply the regulator with a regulating voltage magnitude linked with the detection signal.

11. Apparatus as claimed in claim 10, wherein the regulator has a proportional-integral-differential characteristic.

12. Apparatus as claimed in either claim 10 or claim 11, wherein the filter is connected at its input to said connection upstream of a setting member of the regulator with respect to the signal flow direction from the detector to the exciter.

13. Apparatus as claimed in any one of the preceding claims, wherein the carrier is supported by stationary support means to be pivotable about an axis and the oscillator is arranged to oscillate by resilient deformation of at least part thereof in a plane substantially perpendicular to the axis.

14. Apparatus as claimed in claim 13, wherein the oscillator comprises two limbs defining passage means as the fluid chamber and each comprising a portion fixed at the carrier and a portion oscillatable by the exciter, said axis being disposed to extend in or adjacent to a boundary plane between the fixed limb portions and the oscillatable limb portions and the centre of mass of the carrier substantially on said axis and substantially centrally between the limbs.

15. Fluid density measuring apparatus substantially as hereinbefore described with reference to Figs. 1 to 6 of the accompanying drawings.

16. Apparatus as claimed in claim 15 and modified substantially as hereinbefore described with reference to Fig. 7 of the accompanying drawings.

17. Apparatus as claimed in claim 15 and modified substantially as hereinbefore described with reference to Fig. 8 of the accompanying drawings.

18. Apparatus as claimed in claim 15 and modified substantially as hereinbefore described with reference to Fig. 9 of the accompanying drawings.

19. A method of calibrating apparatus claimed in any one of the preceding claims when the apparatus is to be used for measuring the density of a liquid containing water and alcohol, the method comprising the steps of introducing water and an alcohol of known density into the fluid chamber of the oscillator, inducing oscillation of the oscillator, and determining the magnitudes of or magnitudes dependent on the oscillation period durations.

20. A method as claimed in claim 19 and substantially as hereinbefore described with reference to the accompanying drawings.

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